Soils and Foundations 2013;53(2):272–281

The Japanese Geotechnical Society

Soils and Foundations

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Chemical stabilization of soft Bangkok clay using the blend of calcium carbide residue and biomass ash

Songsuda Vichan, Runglawan Rachan*

Department of Civil Engineering, Mahanakorn University of Technology, 140 Cheumsampam, Bangkok 10530, Thailand

Received 29 July 2012; received in revised form 1 November 2012; accepted 19 November 2012
Available online 13 March 2013

Abstract

The blend of calcium carbide residue (CCR) and biomass ash (BA) required as a stabilizing chemical additive which causes a pozzolanic reaction was investigated. The dissolution of CCR in water generated calcium hydroxide, $Ca(OH)_2$. This high pH solution (pH = 12.6) dissolved the amorphous Si from BA and resulted in pozzolanic products. Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD) analyses indicated the existence of ettringite and non crystalline phase calcium silicate hydrate (C-S-H) after 7 days of curing. The strength development of stabilized clay with a CCR and BA blend is influenced by the interrelationship of various factors, including the binder content, the water content and curing time. From two factorial experiments, the strength of stabilized clay at specific curing time and initial water content was the function of the CCR content, the BA content and their combined effect. When the initial soil water content was constant at 1.2 and 1.4 times the optimum water content (OWC) and the binder contents ranged from 5% to 30% of the dry weight of soil, the strength depended on the clay water–binder ratio (w_c/B) and the curing time. The plot of the strength development ratio and curing time on a logarithmic scale revealed that the blend of CCR and BA rendered a different chemical reaction from cemented clay and fly ash (FA) and BA blended cement admixed clay. The strength development ratio of stabilized clay with a CCR and BA mixture exceeded those of cemented clay and FA and BA blended cement admixed clay after 28 days of curing due to the progress of the pozzolanic reaction.

Keywords: Chemical stabilization; Soft clay; Strength; Calcium carbide residue; Biomass ash; Pozzolanic reaction; Microstructure; Clay water–binder ratio

1. Introduction

Soft Bangkok clay is known as low swelling clay. The swelling potential of such clay increases with depth. It has high water content close to its liquid limit, bringing about settlement and low inherent shear strength (Horpibulsuk et al., 2007). Infrastructure development is sometimes carried out on this soft clay soil due to the difficulties of land acquisition. For road and airfield applications, Rafalko et al. (2007) studied the effectiveness of compaction using cement, quick lime and calcium carbide to increase the unconfined compressive strength of soft clay soils. Treating clay with quick lime and calcium carbide resulted in similar strength gains. They also claimed that calcium carbide could stabilize soil in the same way that hydrate lime did. Some recent research has been conducted on the applications of alternative additives for the stabilization of soft clay. Ahmed et al. (2011) recommended the

*Corresponding author.
E-mail addresses: songsudavichan@gmail.com (S. Vichan), runglawa@gmail.com (R. Rachan).
Peer review under responsibility of The Japanese Geotechnical Society.

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http://dx.doi.org/10.1016/j.sandf.2013.02.007

use of furnace cement type B as a solidification material for stabilization of soft clay with recycled gypsum for embankment. O'Kelly (2011) proposed the mixture of aluminum sulfate and polyelectrolyte solutions as a chemical additive for high-plasticity organic clay.

Calcium carbide residue (CCR) or carbide lime, a byproduct of acetylene manufacturing, dissolves in water and produces $Ca(OH)_2$. An estimated volume of 21, 500 t/year in Thailand's detention pond is considered as an environmental threat (Tanalapsakul, 1998). CCR and hydrated lime are similar in their chemical and mineralogical compositions with the exception of the presence of carbon ($\approx 2\%$) in CCR (Cardoso et al., 2009). In the literatures, many kinds of biomass ash (BA), such as rice husk, wood, wheat straw and sugar cane straw, have been recognized as potential additives in portland cement due to their capacity to react with hydrated lime (Ahmaruzzaman, 2009). In cement admixed clay, it should be noted that an insufficient amount of $Ca(OH)_2$ from hydration means that fly ash (FA) and BA do not act as pozzolanic materials. As such, the role of FA and BA in soil is limited: they are dispersing agents of clay–cement clusters (Horpibulsuk et al., 2009).

Beeghly and Schrock (2009) showed the mixture of lime by products and FA to stabilize the dredge material for structural fill as a result of the pozzolanic and sulfo-pozzolanic reactions. In an earlier study by Horpibulsuk et al. (2012), the cementitious binder from the mixture of CCR and class F FA was shown to enhance the strength of silty clay in the northeast of Thailand. Among the results of preliminary studies on the stabilization of the low water content soft clay, Vichan and Rachan (2010) suggested that improvements in the unconfined compressive strengths of soft Bangkok clay due to the blend of CCR and BA highly depended on several factors: the proportion of CCR and BA, the initial soil water content, the binder content and curing time. With an initial soil moisture content at 1.2 OWC, the use of a 5% binder to stabilize soft Bangkok clay, with a blended binder proportion of CCR:BA = 60:40 rendered the highest strength after 14 days of curing.

Though some research has been done on the application of the blend of CCR and pozzolanic materials as cementitious binders, no research has been focused on the contribution of each material and their interaction in strength development. In the present paper, after discussing the microstructural examination by means of Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD), the effect of each material as well as their combined effect on strength gain was determined by two factorial experiments. Further, by adopting the Clay water–Cement ratio hypothesis (Miura et al., 2001; Horpibulsuk et al., 2003, 2005) the effects of the ratio of clay water to binder content (w_c/B) on strength development at different curing times was investigated. A generalized equation is proposed for predicting the laboratory strength of stabilized clay within a certain range of water contents, binder contents and curing times. Finally, the authors compare the strength development ratio of stabilized clay with this alternative binder to other binders used in previous reports on cement admixed clay and FA, BA blended cement clay (Horpibulsuk et al., 2009, 2011a, 2011b, 2012).

2. Materials used and methodology

2.1. Materials used

2.1.1. Soil sample

Soft clay was collected from the Bangkapi district, Bangkok, Thailand at a 3–5 m. depth. The open-air dried soil was subjected to size reduction by the Los Angeles abrasion machine. Soil samples then were passed through sieve no. 4 and stored in dry containers before use. The soil water content was 8–12% by dry weight of soil. The specific gravity of the soil was approximately 2.76. The liquid and plastic limits were 81% and 35%, respectively. According to the Unified Soil Classification System (USCS), Bangkok clay was classified as a high plasticity clay, fat clay (CH). The maximum dry density (MDD) and the optimum water content (OWC) of raw clay were determined by the Standard Proctor compaction test (ASTM D698) as 14.4 kN/m^3 and 21.5%, respectively.

2.1.2. Binders

The CCR was a grayish white solid. It was generated from a Sai 5 Acetylene gas factory in Nakhon Pathom province. The BA, which was generated from the combustion process of the National power supply plant in Chachoengsao province, was composed of 42% rice husk, 24% bark, 23% eucalyptus chips and 6% board. Both the CCR and BA were ground to smaller sizes by the Los Angeles abrasion machine and passed through sieve no. 325. The specific gravity of CCR and BA were 2.25 and 1.95, respectively. The pH at 20 °C of CCR and BA measured by a lab 850 set Schott pH meter were 12.6 and 9.3, respectively (solid: liquid ratio = 1:2). The chemical compositions of the binders were determined by X-ray fluorescence (XRF), and the results are shown in Table 1.

Table 1
Chemical compositions of binders.

(%) Chemical compositions	BA	CCR
SiO_2	74.12	5.71
Al_2O_3	0.57	2.61
Fe_2O_3	0.88	0.72
CaO	5.91	83.1
MgO	1.54	0.80
SO_3	0.5	0.90
Na_2O	3.33	0.05
K_2O	1.71	0.08
Others	3.90	0.29
LOI	7.45	5.71

2.1.3. Factorial experiments

Two factorial experiments (2^2 experiments) were conducted in order to investigate the interaction and combined effect of the two factors. It was unknown whether the effect of the BA content on the unconfined compressive strength of stabilized clay depended on the CCR content in the soil or vice versa. In an earlier study, it was shown that a dissimilar response or strength results from adding different amounts of binder with another binder at the same time (Montgomery, 1991; Jiju, 2003).

The two sets of 2^2 experiments were designed for different binder contents. For every set of experiment, there were four runs with three replicated tests (Fig. 1). The appropriate initial soil water content is based on results from our previous study (Vichan and Rachan, 2010), in which stabilized clay with a blend of CCR and BA were shown to require a soil water content higher than OWC in order to initiate the pozzolanic reaction. An initial soil water content of 1.2 OWC provided the highest strength. In the present study, the initial water content of the soil samples was adjusted to 1.2 OWC (25.8% by the dry weight of soil) prior to adding the binders. In our study, the 'factor' refers to the type of binder and the 'response' is the unconfined compressive strength. The two primary factors were CCR and BA. Each binder was studied at two different levels, at low and high binder contents in the soil, as described in Table 2. The average values of maximum axial strength at 28 days of curing were plotted in the interaction plot in order to identify the combined effect. Where the lines are parallel in the interaction plot, no interaction between these two factors occurs. The stronger combined or joint effect, the less parallel the lines are (Jiju, 2003).

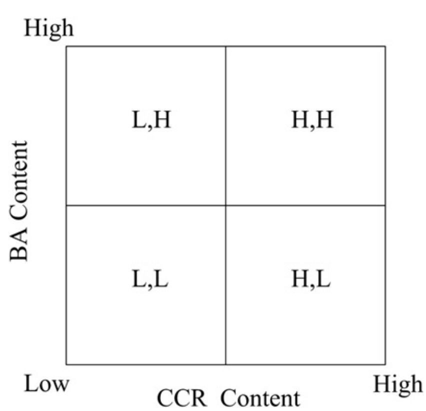

Fig. 1. 2^2 Factorial Experimental Design

Table 2
2^2 Factorial experiments and test combinations.

Experiment	CCR contents	BA contents	Experimental runs (CCR, BA) contents
Set 1	L=0%, H=9%	L=0%, H=6%	L,L=0,0% H,L=9,0% L,H=0,6% H,H=9,6%
Set 2	L=6%, H=18%	L=4%, H=12%	L,L=6,4% H,L=18,4%; L,H=6,12% H,H=18,12%

L=Low Level, H=High Level.

If the interaction of CCR and BA contents is present, the unconfined compressive strength of stabilized clay at any curing time (q_D) should be expressed as the function of CCR contents (B_1) BA contents (B_2) and interaction of CCR and BA contents ($B_1 \times B_2$).The equation is given below.

$$q_D = f(B_1, B_2, B_1 \times B_2) \quad (1)$$

2.1.4. Multiple regression analysis (MRA)

The factorial experiments are simply assumed to produce a linear response due to the type and amount of the factor chosen. The content of the binder that providing the linear strength development was determined, in the range of 5% to 50% by dry weight of the soil as observed at 7, 28, 60, 90 and 150 days of curing. These results reveal the optimal range of binder contents for MRA. The MRA was carried out by the Statistical Package for the Social Sciences (SPSS) to predict the unconfined compressive strength of the stabilized clay at certain curing times, due to the amount of binder and the combined effect.

2.1.5. Mixing proportions

Different mixing proportions of soil, CCR and BA were designed to study the combination of clay water content and binder content that contributed to the development in strength. The initial soil water contents were adjusted to 1.2 and 1.4 OWC (25.8% and 30.1% respectively). From our previous work, the most suitable proportion of CCR and BA to stabilize soft Bangkok clay was set at 60:40 (Vichan and Rachan, 2010). The soil samples were then mixed with dosage of 5%, 8%, 10%, 12% and 15% binder (CCR:BA=60:40) by dry weight soil. Clay and binders were mixed throughly for 10 min (Miura et al., 2001). Hence, w_c/B were in the range of 1.72–6.02. The effects of parameter w_c/B on the unconfined compressive strength were studied at 14, 28, 60 and 90 days of curing.

2.1.6. Laboratory test

The unconfined compression tests (ASTM D 2166-85) were performed for both raw and stabilized clay. The completed mixed samples were compacted in a cylindrical mold, 50 mm in diameter and 100 mm in height with Standard Proctor compaction energy (ASTM D 698). There were eight replicated units with the same mixing design and curing conditions to ensure the reliability of the results ($\overline{x}/SD \leq 10\%$). All sample units then were cured in a plastic seal under controlled temperatures at 20 ± 1 °C until the testing date. The unconfined compression tests were carried out at a vertical displacement rate of 1 mm/min.

2.1.7. Microstructural study

The mixture of CCR and BA at the optimum ratio (CCR:BA=60:40) was dissolved in water and cured in a plastic sheet under the controlled temperatures (20 ± 1 °CC) until the testing dates. The morphology of CCR, BA and the blend of CCR and BA were investigated by SEM with the Energy Dispersive X-ray Spectroscopy (EDS) unit. Images from the SEM with EDS analysis revealed the microstructural changes and information on cementitious products from the pozzolanic reaction. The XRD, Bruker AXS Model D-8 Discover results provided information about the chemical compounds found in the raw materials (CCR and BA) and the pozzolanic products produced by the chemical reaction between CCR and BA. The samples were ground into powder before XRD measurements were taken. The measurement conditions covered an angular ranging between 3° to 65°(2θ), with a step size 0.02° and a scan time 0.5 s per step. The microstructural changes and XRD patterns of the blended materials due to the progress of pozzolanic reaction were observed by SEM and XRD at 7, 28 and 90 days of curing.

3. Results and discussion

3.1. Microstructure of the CCR and BA mixture

SEM images reveal that the morphology of the CCR and BA mixture differs according to curing time. The SEM images of CCR and BA are shown in Fig. 2. Fig. 3 presents the XRD patterns of CCR and BA. The XRD pattern of CCR shows the main crystalline phase of portlandite, calcite and carbon. The detected crystalline substances in BA are quartz and cristobalite. The diffuse refraction of XRD pattern of BA at $22^\circ<2\theta<26^\circ$ represents the amorphous Si in BA (Anderson et al., 2000; Davarz and Gunduz, 2005). The microscopic changes in morphology are due to the chemical reaction which occurs when the blended CCR and BA binder came into contact with water. The morphology of the blended binder at 7, 28 and 90 days of curing are shown in Fig. 4. Flaky crystals are observed at 7 days of curing (Fig. 4a), and at 28 days, fibrous like crystals (Fig. 4b) are observed in some part of

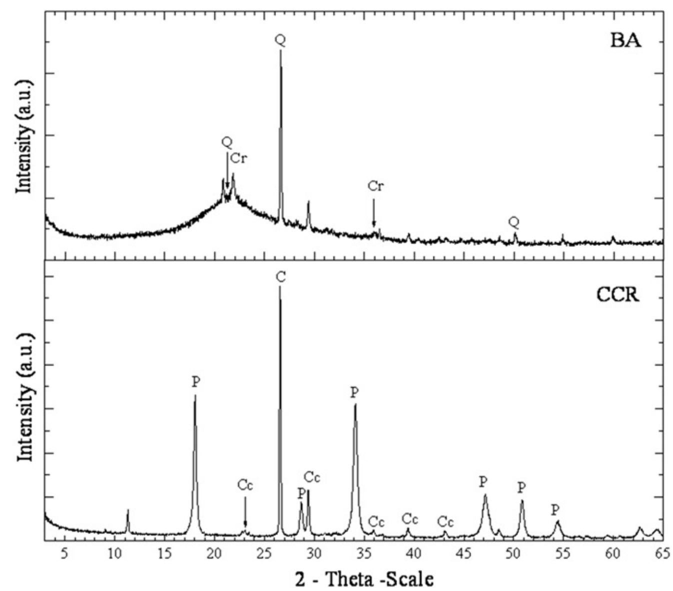

Fig. 3. XRD patterns of raw materials; CCR and BA (C: carbon, Cc: calcite, P: portlandite, Cr:cristobolite and Q:quartz).

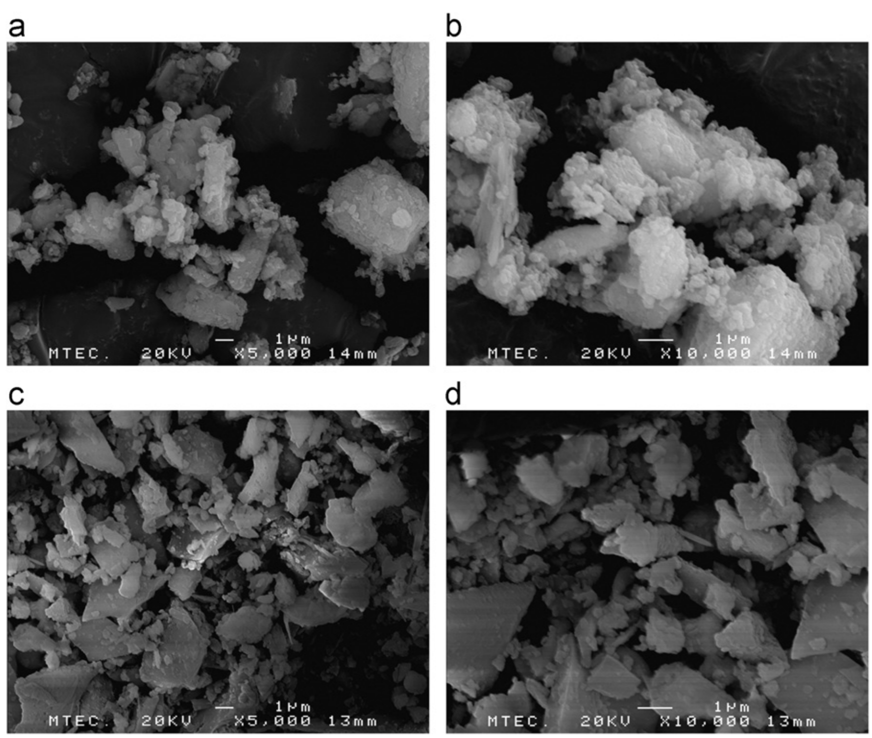

Fig. 2. SEM images of CCR (a) and (b); BA (c) and (d).

sample. At 90 days of curing, the general morphology of sample shows foil like crystals (Fig. 4c). The EDS analysis of these crystals demonstrates that their main compositions are Ca, Si and O.

The XRD patterns of blended binder at 7–90 days of curing are shown in Fig. 5. Even when the curing time is longer, little difference was noted in the XRD patterns of samples. Each pattern clearly shows main peaks of CCR (portlandite and calcite) and BA (quartz and cristobalite). The peaks of sulfo-pozzolanic product, ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$) are identified at 9.091° and 15.784° 2θ after 7 days of curing. In all samples, no C-S-H compounds were identified by XRD. The poor crystalline structures of C-S-H compounds make them undetectable by XRD. The intensities of portandite peaks at several 2θ positions is lower with longer curing times. On the contrary, the intensities of the quartz and cristobalite peaks remain the same as curing progresses, indicating that portlandite does not react with the Si from either the quartz or the cristobalite. This means amorphous Si of BA is more reactive than quartz and cristobalite in dissolution when subjected to the high pH solution of Ca $(OH)_2$. This

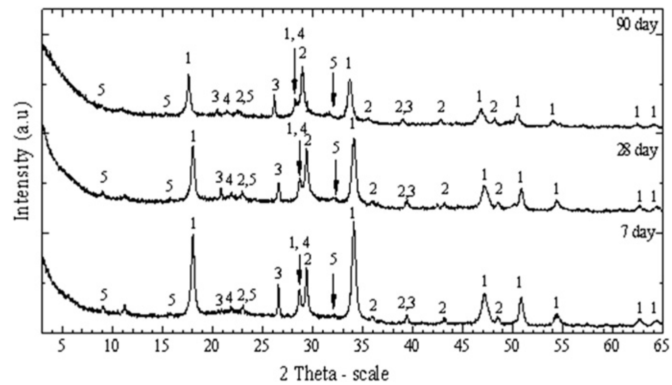

Fig. 5. XRD patterns of blended CCR and BA (CCR:BA=60:40) at 7, 28 and 90 days of curing (1=Portlandite, 2= Calcite, 3 =Quartz, 4=Cristobalite, 5=Ettringite).

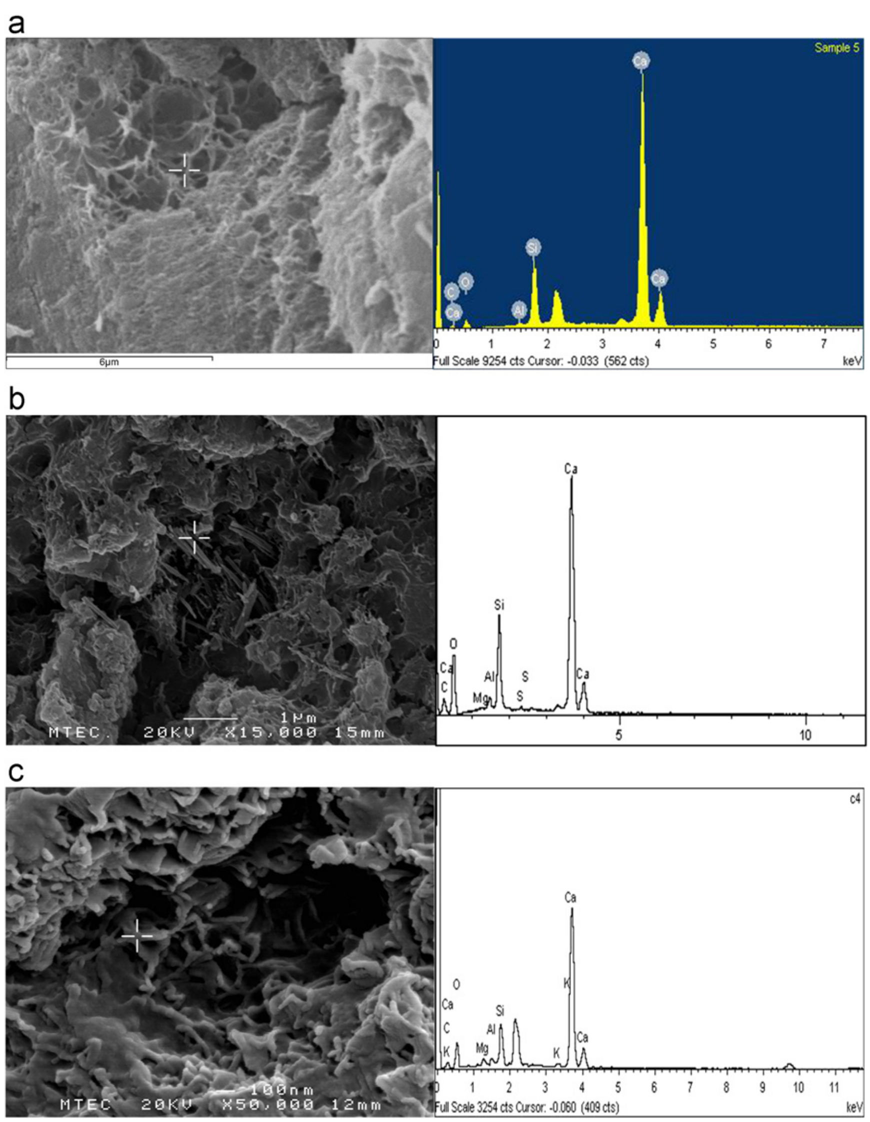

Fig. 4. SEM images and EDS of the blended CCR and BA (CCR:BA=60:40) at (a) 7 days (b) 28 days and (c) 90 days of curing.

implies the 60:40 ratio of CCR:BA improves the strength of soft clay due to the generation of C-S-H from the pozzolanic reaction. It should be noted that this cementitious product and calcium alumino silicate hydrate (C-A-S-H) were also found in cement treated soft Bangladesh clays (Rahman et al., 2010).

3.2. Interaction of CCR and BA

The interaction plot in Fig. 6 demonstrates a great response in strength gain to the addition of both CCR and BA at the same time in soft clay at 28 days of curing. The non-parallel lines of the interaction plot indicate the combined effect of these materials. At no point do the lines cross each other. In addition, the greatest distance between these two lines is observed when the CCR content is increased from 0% to 9%. The difference in strength gain between sole addition of 6% BA and untreated clay is 52 kPa (382–330 kPa). By adding CCR at 9% binder and BA at 6% binder together, the strength is 260 kPa (763–503 kPa), which is considerably higher than the sole addition of CCR.

In stabilizing clay with BA alone, a slight increase in strength gain results from the low basic soil solution (pH = 9.3). The hydrolysis of CCR in either stabilized clay with CCR alone or the blend of CCR and BA results in a very high pH solution (pH = 12.6). Tang and Han (1981) examined the effect of $Ca(OH)_2$ solution on dissolution of amorphous Si. They found that the rapid dissolution of amorphous Si occured when the pH reached 12.5 at room temperature. A similar effect of pH has also been observed in the dissolution of Al (Shi and Day, 2000). Hence, the strength gain in CCR stabilized clay is considerably higher in than that in BA-only stabilized clay and untreated clay. Clay stabilized with a blend of CCR and BA had higher strength than that of CCR stabilized clay because of the supplement in reactive amorphous Si from BA.

Fig. 7 also illustrates the non-parallel and non-crossing lines of the interaction plot which indicate the synergistic effect of these two materials when the binder content increases from 10% to 30%. The combination of the high level of CCR and BA (18% CCR and 12% BA) results in the highest strength among the three. This figure also demonstrates that the increase in the binder contents from 10% to 30% binder provides higher strength in soft clay as a result of the large amount of pozzolanic products.

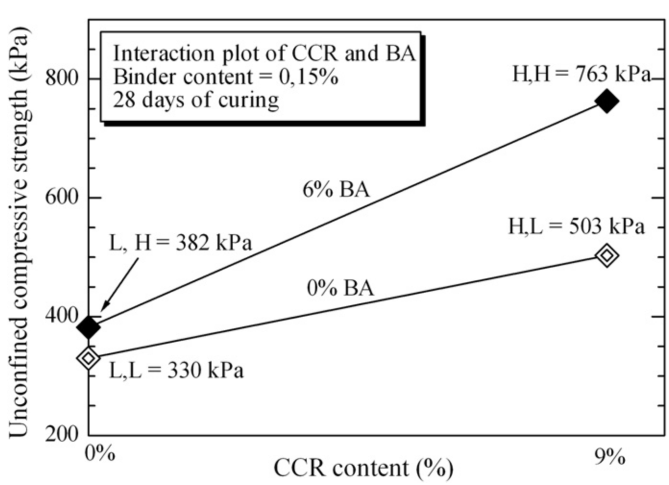

Fig. 6. Interaction Plot of CCR and BA at 0–15% binder content.

3.3. MRA

Fig. 8 demonstrates the pattern of strength improvement in stabilized clay at an initial water content of 1.2 OWC due to the increase in the binder content. A binder content of up to 15% results in considerable improvement in strength after 7 days of curing. The binder content ranges from15 to 30% produce a slight difference in strength improvement. A decline in strength development is clearly observed when the binder content exceeds 30%. A similar response in strength development with the same amount of the blended binder is found at other curing times as well. Strength improvement of stabilized clay can be divided

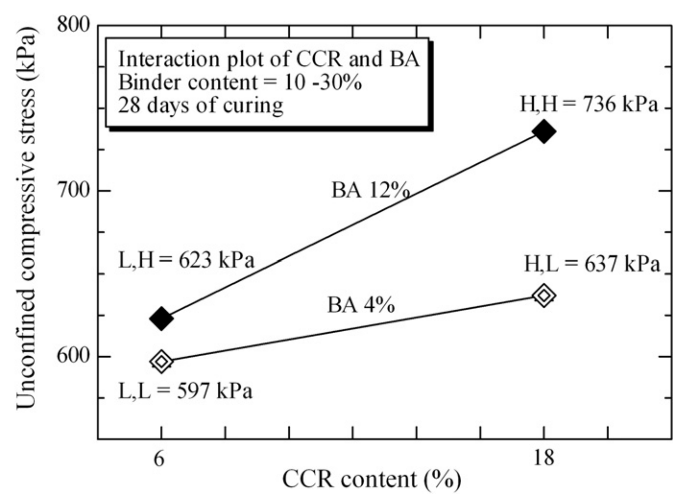

Fig. 7. Interaction Plot of CCR and BA at 10–30% binder content.

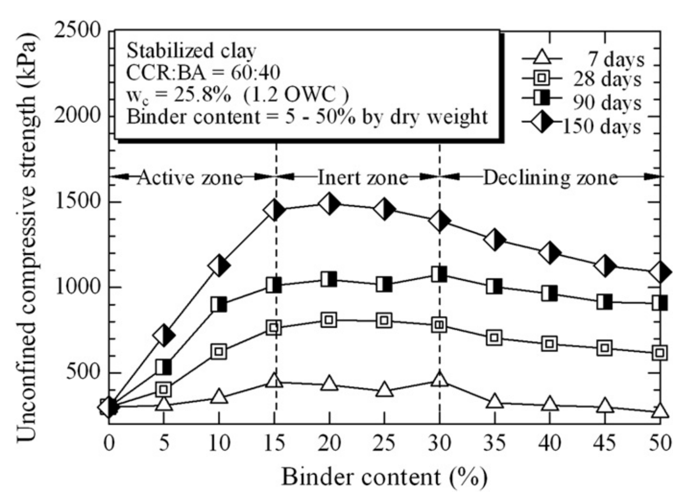

Fig. 8. The effect of binder content on strength development.

into three zones: an active ($B<15\%$), inert ($B=15$–30%) and declining zone ($B>30\%$). In the active zone, there is sufficient SiO_2 content from the BA and clay for a chemical reaction with $Ca(OH)_2$ from CCR to occur. When the binder content exceeds 15%, the strength improvement is negligible, or, at least diminishes. This behavior is similar to concrete with high free lime content. Therefore, the excess lime from CCR results in unsoundness and poor strength development in stabilized soil. The progress in dissolution of silica and alumina from BA and the pozzolanic reaction with $Ca(OH)_2$ generate more cementitious products after 28 days of curing. For that reason, a longer curing period produces higher strength in stabilized clay.

It should be noted that the simultaneous addition of CCR and BA at binder contents of up to 15% is the studied range for MRA. A change in the contents of one binder material has a significant impact on the strength gain response from another material. Hence, the relationship between the binder content (B) and the unconfined compressive strength at any particular curing time (q_D) depends on the CCR content (B_1), BA content (B_2) and the interaction of these two materials ($B_1 \times B_2$) and can be expressed as follows,

$$q_D = a_1(B_1) + a_2(B_2) + a_3(B_1 * B_2) + C \quad (2)$$

where q_D is the unconfined compressive strength of stabilized clay at D day of curing, B_1 is the percentage of CCR in the dry weight of the soil and B_2 is the percentage of BA content by in the dry weight of the soil.

When the initial water content in the soil was constant at 1.2 OWC and the CCR:BA ratio was fixed at 60:40, the unconfined compressive strength data of soft Bangkok clay with the test combinations shown in Table 3 was subject to the MRA. The regression equations were evolved to predict the strength at different binder contents. The calculated strength developments at certain curing times from SPSS program (using stepwise method and $\alpha=0.05$) are demonstrated in Table 4.

From an MRA analysis, the constant a_1 presented a change in strength gain due to the independent variable, B_1 only when the variables B_2 and $B_1 \times B_2$ were fixed. If the value of B_1 is increased by 1%, the strength of stabilized clay increases by approximately a_1 kPa. The relationships between variables B_2, $B_1 \times B_2$ and strength were similar to that of B_1. Furthermore, a_1, a_2 and a_3 increased with the curing time. Thus, the strength gain from every 1% increment of binder content is higher when the curing time is longer.

Table 3
The experimental design and test combinations.

B (%)	B_1 (%)	B_2 (%)	$B_1 \times B_2$ (%)	Curing times
0	0	0	0	28 days ($N=60$)
5	3	2	6	
6	0	6	0	60 days ($N=39$)
8	5	3	15	
9	9	0	0	90 days ($N=90$)
10	6	4	24	
12	7	5	35	150 days ($N=60$)
15	9	6	54	

B=% Binder content, B_1=% CCR, B_2=%BA, N=numbers of data.

Table 4
MRA equations at 28, 60, 90 and 150 days of curing.

Curing time (days)	Regression equation	Adjusted R^2
28	$q_{28}=30.85\ (B_1)+17.79\ (B_2)+1.93\ (B_1 \times B_2)+291.04$	0.935
60	$q_{60}=36.47\ (B_1)+33.54\ (B_2)+3.00\ (B_1 \times B_2)+298.74$	0.986
90	$q_{90}=41.44\ (B_1)+52.10\ (B_2)+1.68\ (B_1 \times B_2)+317.42$	0.926
150	$q_{150}=75.75(B_1)+76.40\ (B_2)+2.47\ (B_1 \times B_2)+297.53$	0.980

3.4. Analysis of the relationships of clay water–binder ratio, curing time and strengths

The initial soil water content and the binder content are considered as the clay water–binder ratio, w_c/B. Fig. 9 presents the relationship of parameter w_c/B and q_D at 14, 28, 60 and 90 days of curing. The strength of stabilized clay is a function of w_c/B. An increase in parameter w_c/B results in a reduction in strength at all curing times.

The relationship between parameter w_c/B and strength in the power function is demonstrated as the following.

$$q_D = \frac{A}{(w_c/B)^E} \quad (3)$$

where q_D is the unconfined compressive strength at any specific curing time (kPa unit), w_c/B is the ratio of the water content in clay to the percentage of blend binder in the dry weight of soil. The constant A (kPa unit) increases with curing time. The effect of parameter w_c/B on strength is influenced by the unitless constant, E. The values of constant E relate to the type of clay and binder. For soft Bangkok clay, the constant E signifies the pozzolanic reaction between the blend of CCR and BA and clay water. The value of constant E at 14 days of curing (0.27) is much lower than those of 28, 60 and 90 days of curing. After 28 days of curing, the values of constant E are quite similar ($E=0.55$–0.60). For the stabilization of soft Bangkok clay with blended CCR and BA, the general equation of strength at 28–90 curing days with average constant E is:

$$q_D = \frac{A}{(w_c/B)^{0.58}} \quad (4)$$

At a certain curing period, the ratio of strength generated by the different w_c/B values becomes the function of the parameter w_c/B ratio only when the constant A is eliminated. When the strength at any w_c/B is determined in

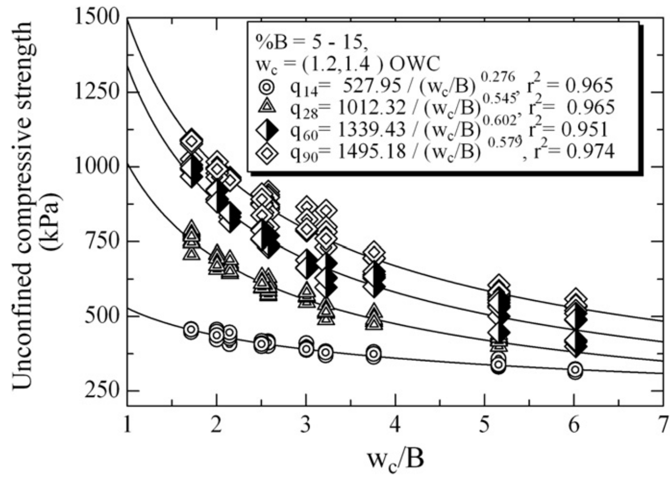

Fig. 9. The effect of parameter on unconfined compressive strength at 14, 28, 60 and 90 days of curing.

a laboratory test, the strength at the same curing time and with other w_c/B values can be estimated according to the following relationship:

$$\frac{q_{(w_c/B)_1}}{q_{(w_c/B)_2}} = \left[\frac{(w_c/B)_2}{(w_c/B)_1}\right]^{0.58} \tag{5}$$

where $q_{(w_c/B)_1}$ is the predicted strength of the stabilized clay at a clay water/binder of $(w_c/B)_1$ and $q_{(w_c/B)_2}$ is the laboratory strength at a water/binder of $(w_c/B)_2$.

The w_c/B parameter and the curing time both play a significant role in strength development, as depicted in Fig. 10. The effects of curing time on the improvement in strength with different values of w_c/B present a linear relationship. The lower the w_c/B parameter, the steeper the slope. Further, an increase in the curing time enhances the strength of stabilized clay. For this reason, the strength of stabilized clay depends on the interrelationships among the ratio of clay water to the binder content and the curing time.

Fig. 11 shows the plot of the strength development ratio ($q_D/^Dq_{28}$) and the curing time on a logarithmic scale. It provides a generalized strength development equation of stabilized soft clay with a blend of CCR and BA. Providing the type of soil and binder are not changed, the increase in strength with time for any w_c/B values should be equal since the same chemical reaction occurs. The generalized equation for stabilizing soft Bangkok clay with a blend of CCR and BA (CCR:BA = 60:40) and w_c/B range of 1.72–6.02 is demonstrated below:

$$q_D/^Dq_{28} = 0.366\ln D - 0.213 \tag{6}$$

The variations of parameter w_c/B together with the curing time account for strength development as demonstrated by a combination of Eqs. (5) and (6). Thus, the strength of the stabilized clay for w_c/B values ranging from 1.72 to 6.02 can be determined by Eq. (7)

$$\left\{\frac{q_{(w_c/B)_D}}{q_{(w_c/B)28}}\right\} = \left[\frac{(w_c/B)_{28}}{(w_c/B)_D}\right]^{0.58}(0.366\ln D - 0.213) \tag{7}$$

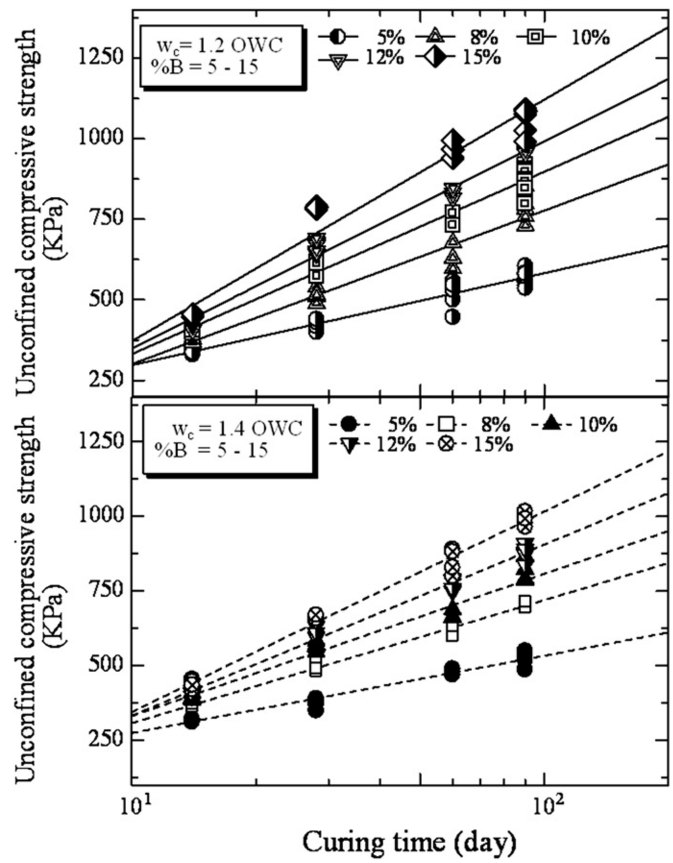

Fig. 10. The development of unconfined compressive strength with curing times.

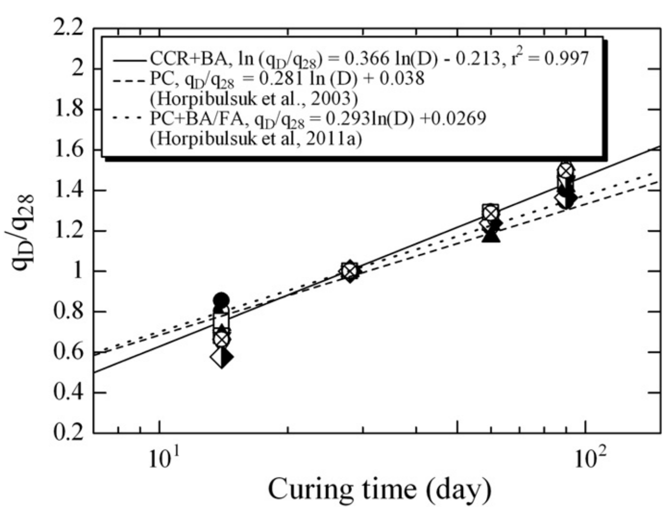

Fig. 11. Strength development rate and curing time of stabilized clay with the blended CCR and BA.

where $q_{(w_c/B)_D}$ is the predicted value of strength at any $(w_c/B)_D$ after D days of curing and $q_{(w_c/B)_{28}}$ is the known value, or reference strength, at $(w_c/B)_{28}$ after 28 days of curing. It should be note that all constants in Eqs. (4) to (7) are valid only for clay stabilized with a CCR:BA ratio of 60:40.

While Horpibulsuk et al. (2003, 2011a and 2011b) found that a blend of CCR and BA for stabilizing clay provided similar results to cement and FA or BA blended cement with regard to the relationship of strength development ratio ($q_D/^Dq_{28}$) and curing time, the results of this study show no similarity. In this study, the development in the strength of stabilized clay with a blend of CCR and BA was shown to be the consequence of cementitious products from different chemical reactions. It is not the hydration reaction (with minimal pozzolanic reaction) which provides the strength of the blended cement admixed clay, as Horpibulsuk et al. (2009) claimed. The strength development of clay stabilization with a blend of CCR and BA is more pronounced than those of stabilized clay with cement and FA or BA blended cement. This clearly indicates that it is not the hydration reaction but the pozzolanic reaction that contributes to the strength in stabilized clay.

4. Conclusion

The stabilization of soft Bangkok clay with a blend of CCR and BA improves the unconfined compressive strength via the pozzolanic reaction. Improvements in the strength of clay are influenced by a number of factors, including the interrelationship between the ratio of clay water to binder content and the curing time. The present study leads to the following conclusions:

1. The addition of water to a mixture of CCR and BA (CCR:BA = 60:40) was found to foster the pozzolanic reaction at normal temperature and pressure. The SEM images provided an understanding of the changes in morphology as the reaction progressed. The SEM and XRD results showed that amorphous Si from BA dissolved in a high pH solution and then reacted with CCR. Ettringite and non crystalline phase C-S-H are the cementitious products observed at 7 days of curing.
2. At a certain soil water content (1.2 OWC), the change in the level of CCR content in the soil had an influence on the unconfined compressive strength generated by the addition of BA and vice versa. When the binder content was up to 30% of the dry weight of soil, the combined effect of CCR and BA was found to be significant in the strength development of clay.
3. When the blend of CCR and BA content did not exceed 15% (%B $\leq$ 15), multiple regression models were proposed for the determination of unconfined compressive strengths at 28, 60, 90 and 120 days in terms of CCR content (B_1), BA content (B_2) and their interaction ($B_1 \times B_2$).
4. A clear interrelationship was found between the clay water–binder ratio, curing time and strength. The strength behavior of stabilized clay with a blend of CCR and BA was compiled with the clay water–cement ratio hypothesis and expressed as a power function. The pozzolanic reaction between the blend of CCR and BA and water in the clay generated the strength development with time. For soft Bangkok clay, the generalized equation for strength prediction at 28–90 days of curing was proposed at any w_c/B range from 1.72 to 6.02.
5. The change in strength development ratio with curing time indicated the main reaction that produced the strength in stabilized clay. The development ratio of stabilized clay with the blend CCR and BA after 28 days of curing was considerably higher than those of cemented clay, FA or BA blended cement clay as a result of the substantial progress of the pozzolanic reaction.

Acknowledgment

The authors would like to acknowledge the financial support, laboratory equipments and facilities provided by Civil Engineering Department, Mahanakorn University. The technical assistance in XRD examination of Mr. Manop Tirarattanasompot of Scientific and Technological Research Equipment Center, Chulalongkorn University is highly appreciated. Grateful acknowledgment is also given to Miss Acharaporn Srion of the National Metal and Materials Technology Center for her skillful assistance with SEM examination.

References

Ahmaruzzaman, M., 2009. A review on the utilization of fly ash. Progress in Energy and Combustion Science, 1–37.

Ahmed, A., Ugai, K., Kamei, T., 2011. Laboratory and field evaluations of recycled gypsum as a stabilizer agent in embankment construction. Soil and Foundations 51 (6), 975–990.

Anderson, D., Roy, A., Seals, R.K., Carledge, F.K., Akhter, H., Jones, S.C., 2000. A preliminary assessment of the use of an amorphous silica residual as a supplementary cementing material. Cement and Concrete Research 30, 437–445.

Beeghly, J., Schrock, M., 2009. Dredge material stabilization using the pozzolanic or sulfo-pozzolanic reaction of lime by-products to make an engineered structural fill. International Journal of Soil, Sediment and Water 3 (1), 6.

Cardoso, F.A., Fernandes, H.C., Pileggi, R.G., Cincotto, M.A., John, V.M., 2009. Carbide lime and industrial lime characterization. Powder Technology 195, 143–149.

Davarz, M., Gunduz, L., 2005. Engineering properties of amorphous silica as a new natural pozzolan for use in concrete. Cement and Concrete Research 35, 1251–1261.

Horpibulsuk, S., Miura, N., Nagaraj, T.S., 2003. Assessment of strength development in cement admixed high water content clays with Abraham's law as a basis. Geotechnique 53 (4), 439–444.

Horpibulsuk, S., Miura, N., Nagaraj, T.S., 2005. Clay–water/ cement ratio identity of cement-admixed soft clay. ASCE Journal of Geotechnical and Geoenvironmental Engineering 131 (2), 187–192.

Horpibulsuk, S., Shibuya, S., Fuenkajorn, K, Katkan, W., 2007. Assessment of engineering properties of Bangkok clay. Canadian Geotechnical Journal 44 (2), 173–187.

Horpibulsuk, S., Rachan, R., Raksachon, Y., 2009. Role of fly ash on strength and microstructure development in blended cement stabilized silty clay. Soil and Foundations 49 (1), 85–98.

Horpibulsuk, S., Rachan, R., Suddeepong, A., Chinkulkuniwat, A., 2011a. Strength development in cement admixed Bangkok clay: laboratory and field investigations. Soil and Foundations 51 (2), 239–251.

Horpibulsuk, S., Rachan, R., Suddeepong, A., 2011b. Asessment of strength development in blended cement admixed Bangkok clay. Construction and Building Materials 25, 1521–1531.

Horpibulsuk, S., Phetchuay, C., Chinkulkijniwat, A., 2012. Soil stabilization by calcium carbide residue and fly ash. ASCE Journal of Materials in Civil Engineering 24 (2), 184–193.

Jiju, A., 2003. Design of Experiments for Engineers and Scientists. Elsevier Ltd., UK.

Rafalko, S.D, Brandon, T.L., Filz, G.M., Mitchell, J.K., 2007. Rapid chemical stabilization of soft clay soils. In transportation research record. Journal of the Transportation Research Board 2026, 39–46.

Miura, N., Horpibulsuk, S., Nagaraj, T.S., 2001. Engineering behavior of cement stabilized clay at high water content. Soils and Foundations 41 (5), 33–45.

Montgomery, D.C., 1991. Design and Analysis of Experiments, 3rd edition John Wiley & Sons, Inc., New York.

O'Kelly, B.C., 2011. Effects of aluminum sulfate and polyelectrolyte solutions on the geotechnical properties of organic clay. Soils and Foundations 51 (2), 359–367.

Rahman, M.M., Siddique, A., Uddin, K., 2010. Microstructure and chemical properties of cement treated soft Bangladesh clays. Soils and Foundations 50 (1), 1–7.

Shi, C., Day, R.L., 2000. Pozzolanic reaction in the presence of chemical activators Part II. Reaction products and mechanism. Cement and Concrete Research 30, 607–613.

Tang, M., Han, S., 1981. Effect of $Ca(OH)_2$ on alkali–silica reaction. Journal of Chinese Silicate Society 9 (2), 160–166.

Tanalapsakul, A. (1998). Document from M Thai industrial company limited. M Thai Industrial Co.Ltd., Samutsakorn, Thailand.

Vichan, S., Rachan, R., 2010. Potential use of calcium carbide residue and biomass flyash as cement substitution for soil stabilization. In: Proceedings of the International Symposium on Lowland Technology, Saga University, Saga, Japan, pp. 98–103.